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SEASONAL TRENDS OF RAINFALL AND SURFACE TEMPERATURE OVER SOUTHERN AFRICA

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ABSTRACT This study investigated seasonal trends of surface temperature and rainfall from 1979 to 2007 in southern Africa. In recent years, annual rainfall has decreased over the African continent from the equator to 20°S, as well as in Madagascar. On the other hand, annual mean surface temperature has shown an increasing trend across the whole region, with particularly large rates of increase in Namibia and Angola. The spatial and temporal structures of trends in rainfall and surface temperature have apparent seasonality, with rainfall in Angola, Zambia, and Namibia tending to decrease from December to March, and surface temperature from Namibia to southeastern South Africa tending to increase from July to October. To clarify the relationship between the seasonal trend and the interannual variation of the seasonal march of rainfall, empirical orthogonal function (EOF) analysis was applied to pentad rainfall data. The first and second modes of temporal structures showed strong seasonality, and their seasonal marches modulated after 1987 and 1995, respectively. These modulations included delay in rainy season onset, early withdrawal of the rainy season, and weak rainfall.

Key Words: Seasonal trend; Rainfall; Surface temperature; Seasonal march; Modulation.

INTRODUCTION

Environmental changes associated with global warming have been investigated from various research perspectives. Numerous studies have examined trends and interannual variations of rainfall. Such studies are particularly important in southern Africa, which has an extensive dry region and sparse water resources. Fauchereau et al. (2003) examined rainfall variability and change during the 20th century in the context of global warming. They reported that although there were no long-term trends of cumulative summertime rainfall anomalies in South Africa, rainfall variability in southern Africa has experienced significant modulations, especially in recent decades. In particular, droughts have become more intense and widespread. New et al. (2006) reported a decrease in average rainfall intensity and an increase in dry-spell length from 1961 to 2000. Furthermore, a recent report by the Intergovernmental Panel on Climate Change (IPCC, 2007) showed an increasing trend in rainfall amount from 1901 to 2005 from the equator to tropical eastern Africa but a decreasing trend south of 20°S on the African continent. However, the report also noted that these tendencies were obscure during 1979 and 2005.

These studies and reports suggest that annual rainfall has not had a clear

tendency in the last 20 or 30 years, but dry periods in southern Africa have become longer and more intense. If these phenomena are occurring as suggested, then the rainfall amount and intensity in the wet season may have increasing trends. In this study, we reconfirm recent trends of annual rainfall and mean surface temperature by region and clarify relationships to the spatial and seasonal structures of these trends. We particularly focus on the interannual variation of the seasonal march of rainfall and discuss its spatial and temporal connection to the tendency of annual rainfall.

DATA AND METHOD

Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP) and National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data were used as the rainfall and surface temperature data, respectively, for the period 1979–2007 (Xie & Arkin, 1996; Kalnay et al., 1996). We selected the “enhanced” CMAP data for this study. CMAP $2.5^\circ \times 2.5^\circ$ grid data were used to obtain the daily mean rainfall intensity in each pentad, and T62 Gaussian grid data from the NCEP Reanalysis Daily Averages Surface Flux dataset at 2m were adopted as surface temperature and converted to a pentad value to reconcile the periods. Sequential numbers, starting from 1 January, were given to each pentad in a year. The value of the twelfth pentad was calculated over 6 days. As the study area was from the equator to 37.5°S and from 5°E to 55°E , 300 and 514 grids were used for the rainfall and the surface temperature, respectively.

To clarify simultaneous seasonal trends and their spatial characteristics for rainfall and surface temperature, we conducted singular value decomposition (SVD) analysis. SVD analysis is an algebraic technique used to decompose arbitrary matrices into orthogonal matrices. It is a powerful tool for identifying sets of relationships between different fields (Bretherton et al., 1992). However, the result detected from the analysis is affected by differences in field size and the magnitude of variance in each field. To reduce the field size of the surface temperature data set, we used 257 grids with a 4° longitudinal interval for the data mentioned above. The study area, which extends from low to middle latitude zones, also had large differences in climate variations by latitude or climate zone. To focus on the seasonal trend of the anomalies in each region rather than on the absolute magnitude of the tendency, SVD analysis was applied to the pentad trend data for standardized anomalies.

Next we investigated the seasonal march of rainfall to understand its relationship to the seasonal trend. For this purpose, we applied empirical orthogonal function (EOF) analysis to the pentad rainfall data in the same area and periods used to detect the spatial and temporal structure.

To clarify the relationship between the interannual variation of the seasonal march of rainfall and other climate factors, a composite analysis was also conducted using the geopotential height at the 850hPa level.

RESULT AND DISCUSSION

I. Recent Trends of Annual Rainfall and Surface Temperature

Figure 1 shows the decadal trends of annual rainfall and annual mean surface temperature from 1979 to 2007. Negative trends of annual rainfall extend to the north of 10°S over the continent, centered from Angola to Malawi. The eastern coastal area of Madagascar also shows a significantly negative tendency. On the other hand, there are no apparent trends over the continental region south of 20°S, except in the northeastern part of South Africa. Figure TS.9 in the “Technical Summary” of the IPCC’s Physical Science Basis report (IPCC, 2007) shows a strong negative trend in the coastal region of northern Namibia. However, this tendency is not shown in our Figure 1a. The IPCC report also shows a positive trend around southeastern Namibia and the coast of Mozambique. These areas

with positive tendencies agree well with our results. For surface temperature, positive trends occur over almost the entire study area, with relatively strong signals over the western part of the continent from Namibia to Angola.

To understand the relationship of these trends to the interannual variation in annual rainfall, the cross-sectional charts with latitudes and time shown in Figure 2 were drawn along the eastern and central parts of the continent and the east coast of Madagascar. In the western and central continental areas, remarkable north-southward gradients of rainfall amounts existed around 15°S before the early 1990s however, the gradients became more gradual after the mid-1990s. This shows that the boundary with relatively little rainfall, indicated as the isohyets from 500–600mm, remained around 20°S throughout the entire period, and that with greater rainfall of 1,000mm shifted northward from 15°S to 10°S after the mid-1990s.

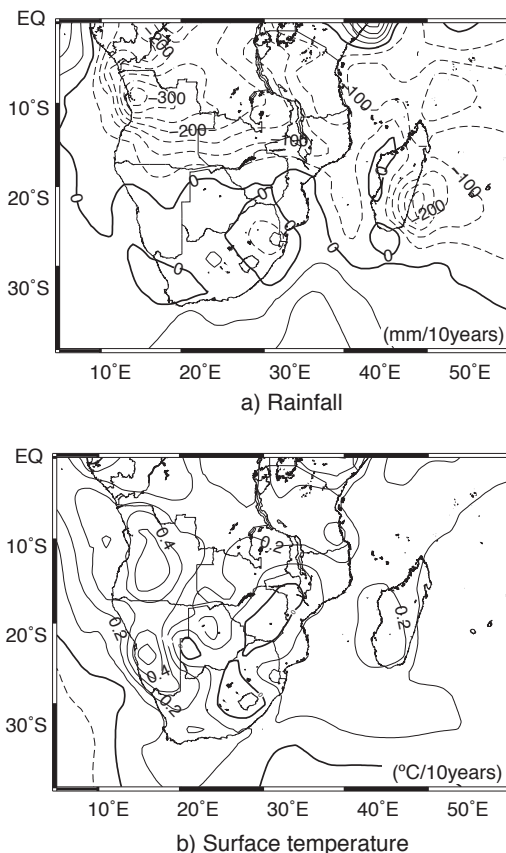


Fig. 1. Decadal trends of annual rainfall and annual mean surface temperature from 1979 to 2007.

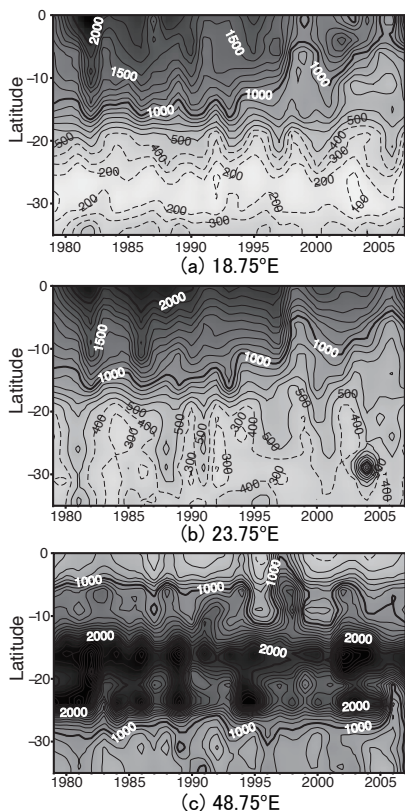


Fig. 2. Cross-sectional charts for annual rainfall amounts with latitudes and time.

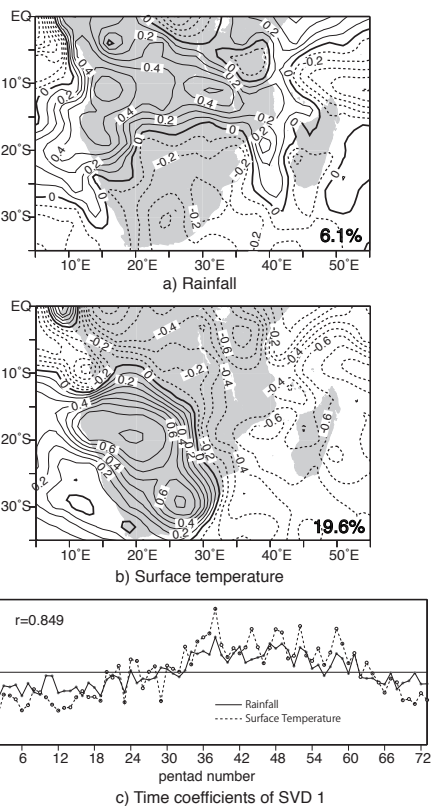


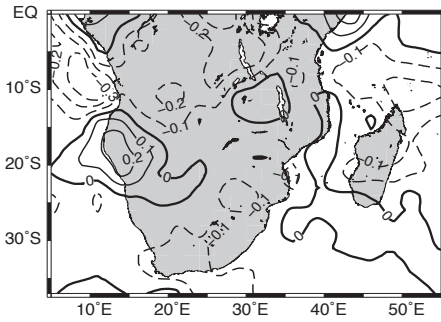
Fig. 3. Homogeneous correlation maps for SVD 1 and their time coefficients.

In the eastern coastal area of Madagascar, rainfall amounts decreased from 15°S to 25°S after the early 1990s, with the southern area experiencing a particularly large reduction of rainfall bands.

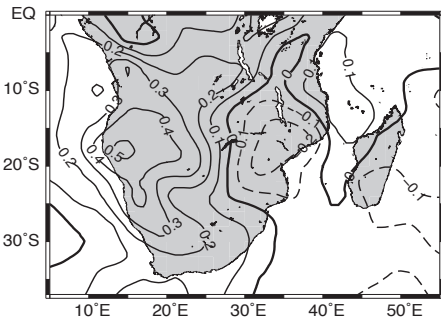
These results suggest that the recent trends of decreasing rainfall in areas north of 20°S reflect an abrupt change around the early 1990s rather than a gradual trend.

II. Spatial and Seasonal Characteristics of the Trends in Surface Temperature and Rainfall

The results of the SVD analysis of the pentad trend data for rainfall and surface temperature indicate that the first mode of the trends (SVD 1) accounts for 33.7% of total covariance, and its temporal variation has an apparent seasonality. Because the lower modes do not have clear seasonality and make small contributions, the first mode is considered to be the only mode with seasonal dependency. Figure 3 shows the simultaneous correlation coefficient maps of SVD 1 and their time coefficients. Figures 4 and 5 present composite maps

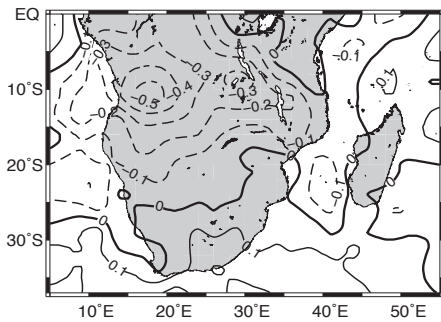


a) Rainfall

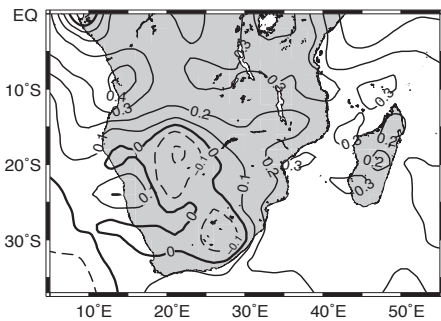


b) Surface temperature

Fig. 4. Composite maps of trends of rainfall and surface temperature for highly positive time coefficients of SVD 1.



a) Rainfall



b) Surface temperature

Fig. 5. Composite maps of trends of rainfall and surface temperature for highly negative time coefficients of SVD 1.

of trends in rainfall and surface temperature for the highly positive and highly negative time coefficients, respectively. Time coefficients one standard deviation above or below the mean were selected as highly positive or highly negative, respectively. There were nine highly positive cases and seven highly negative cases.

Figure 3c illustrates the temporal changes of time coefficients, showing negative values from November to March and positive values from July to October. Because the remarkably positive correlation coefficients for the rainfall field reach from Angola to Zambia and to the northern part of Namibia, the values of the trends in these regions become smaller from November to March and larger from July to October. According to the spatial distributions of trends shown in Figures 4a and 5a, the trends around Angola have negative values in both seasons. Therefore this area has negative trends throughout the year (Fig. 2a), although the magnitudes of the values change seasonally. On the other hand, in the northern part of Namibia, positive trends appear in the case of highly positive time coefficients, and vice versa.

The spatial structure for the surface temperature, illustrated in Figure 3b, shows significantly positive correlation coefficients from Namibia to the southeastern part of South Africa, and negative correlation coefficients along the equator and the eastern coast of the continent, as well as around Madagascar.

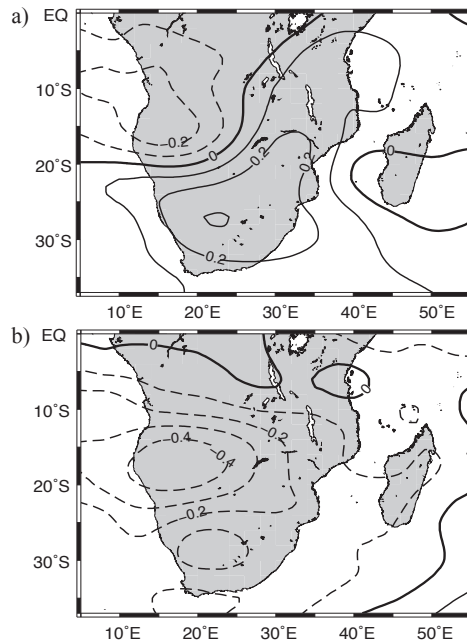


Fig. 6. Composite maps of the trend of standardized geopotential height at 850hPa for highly positive (a) and highly negative (b) time coefficients for SVD 1.

Compared with the composite maps in Figures 4b and 5b, opposite tendencies appear from Namibia to southeastern South Africa and along the continental eastern coast and Madagascar in each season, whereas the same trends extend along the equator.

To investigate the connection of the seasonal trends of rainfall and surface temperature to atmospheric circulation, composite analysis of the trends of standardized geopotential height at 850hPa was conducted for the highly positive and highly negative time coefficients mentioned above. Figure 6 shows composite maps of the trend of geopotential height at 850hPa. In the case of highly positive time coefficients in Figure 6a, which appear mainly from winter to spring, the center of decreasing tendencies is located from the northern part of Namibia to Angola, whereas the increasing center extends east-westward along 30°S and along the eastern coastal region of continent. In the rainfall field, the different trend in geopotential height that occurs around Angola and Malawi is considered to be connected both with the positive trend in the northern part of Namibia and with the negative trend in Angola. Because the lower pressure in the western part of the continent and the higher pressure in the eastern part tend to intensify the northeasterly wind with relatively hot, moist air in northern Namibia, this anomalous wind seems to contribute to the rising trend of surface temperature and rainfall in this area from winter to spring. The increasing trend of pressure around South Africa suggests that lower surface temperature may be produced along the eastern coastal region of the continent by southerly wind

with relatively cold air.

From December to April, as shown in Figure 6b, a decreasing trend of geopotential height develops to the south of 10°S, with a remarkable center around 20°S. The area of this pressure trend coincides with that of the rising trend of surface temperature and the decreasing trend of rainfall. As the relationship between the decreasing pressure trend and the decreasing rainfall trend is difficult to explain by cyclonic activity, the warmer surface temperature suggests an increase in the geopotential height.

The decreasing trend of geopotential height that predominates in the western part of the continent around Angola throughout the year also seems to play an important role in the trends of rainfall and surface temperature.

III. Seasonal March of Rainfall and Its Interannual Variation

To clarify the relationship between the seasonality of the rainfall trend and the interannual variation in rainfall, EOF analysis was applied to the pentad rainfall data from 1979 to 2007. The first and second components detected by this analysis contributed 19.5% and 5.4% to the total variance, respectively. They also included the seasonal cycles in the time coefficients.

The spatial distribution of factor loadings and the time coefficients for the first mode (EOF 1) are shown in Figure 7. Except for the values for southern Africa shown in Figure 7a, which were calculated as the correlation coefficients between the pentad rainfalls and time coefficients, the computation area extended to northern Africa to facilitate interpretation of the spatial distribution. The time coefficients are shown as cross-sectional charts with year and month to explain the interannual variation of the seasonal march.

The spatial structure of factor loadings indicates that the significant correlation coefficients are located around 10°N and 10°S and have different signs in the continental region. Because the time coefficients become positive from May to September and negative from November to March, EOF 1 can be regarded as the component representing the rainfall pattern

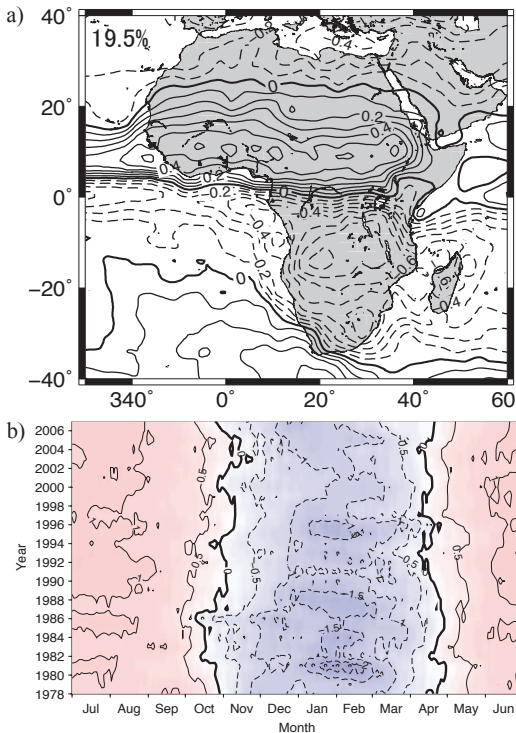


Fig. 7. Spatial distribution of factor loadings and time coefficients for EOF 1.

in the rainy and dry season of each hemisphere. The duration of the negative time coefficient, which expresses the rainy season in southern Africa, appears to become abruptly shorter after 1987, and the intensity also seems to weaken. These results correspond to the shorter and weaker rainy season in southern Africa. The shorter rainy season is considered to result from its delayed onset and early withdrawal. To clarify the change in intensity of the rainfall pattern of southern Africa, the annual number of pentads was counted for the standardized time coefficient below -1 and from -1 to -0.5 . Figure 8 shows the results, which indicate that the number of strong signals with values below -1 decreases one-sidedly, while relatively weak signals from -1 to -0.5 increase gradually. Therefore the amount of rainfall with the spatial pattern, demonstrated in Figure 7a, tends to decrease.

The spatial structure of factor loadings and their time coefficients for EOF 2 are shown in Figure 9, drawn in a similar manner as Figure 7. The significant factor loadings are distributed in the equatorial region, centered on the Congo watershed. The time coefficients have two cycles throughout the year and become negative from September to December and from March to June, coinciding with the start and end of the rainy season in southern Africa, respectively. Accordingly, EOF 2 can be considered to indicate the distinctive rainfall

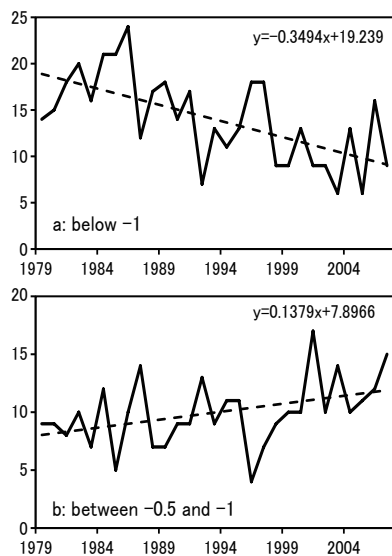


Fig. 8. Interannual variation in the magnitude of time coefficients in the rainy season for EOF 1.

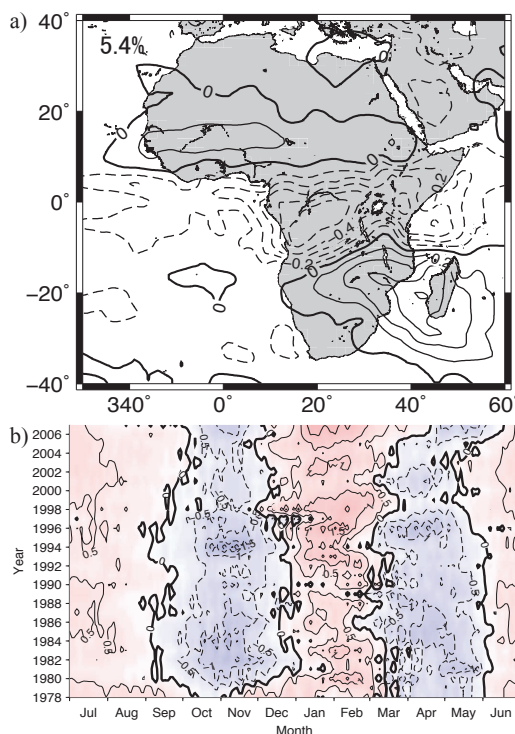


Fig. 9. Spatial distribution of factor loadings and time coefficients for EOF 2.

pattern in the period of seasonal transition between the northern and southern hemispheres. The periods in which the rainy season occurs around the equator (from September to December and from March to June) tend to become shorter, creating longer dry periods. The remarkable change appears after the mid-1990s.

The interannual variations of the seasonal marches for the two EOF modes can be strongly connected with the interannual variation of annual rainfall over southern Africa. According to the cross-sectional charts of annual rainfall for the western coast and middle continental regions shown in Figures 2a and 2b, the annual rainfall amount north of 20°S abruptly decreases after the mid-1990s. The abrupt change of annual rainfall amount corresponds to the shorter rainy seasons after the mid-1990s for EOF 2 and may be affected by the shorter period and weaker rainfall in the rainy season in southern Africa after 1987 for EOF 1.

SUMMARY

This study investigated changes of annual rainfall and annual mean surface temperature over southern Africa in recent years from the point of view of their connection with the seasonal trend and interannual variation of the seasonal march of rainfall. The decreasing trend of annual rainfall was significant to the north of 20°S on the continent and over the eastern coastal area of Madagascar. A remarkable increasing trend of annual mean surface temperature was found around the western coastal region of the continent. Annual rainfall for the west coast and middle parts of the continent north of 15°S decreased abruptly after the mid-1990s, especially in the region with large annual rainfall.

The SVD analysis of the trend of pentad rainfall and surface temperature demonstrated that remarkable seasonality exists for the rainfall trend from Angola to the northern part of Namibia, and for surface temperature from Namibia to southeastern South Africa, along the equator, over the east coast of the continent, and around Madagascar. From winter to spring, the increasing trends of rainfall and surface temperature in the northern part of Namibia seem to be explained by the lower trend of pressure over the western part of the continent and the higher pressure over the eastern part. The decreasing trend of surface temperature along the eastern coastal region of the continent can be explained by the increasing trend of pressure around South Africa. However, from summer to autumn, the apparently decreasing trend of geopotential height south of 10°S is difficult to interpret with regard to the corresponding area with a rising surface temperature trend and decreasing rainfall trend.

The EOF analysis of the pentad rainfall data demonstrated that the first two modes have strong seasonality, and their seasonal marches modulated after 1987 and 1995, respectively. These modulations may play an important role in the decrease in annual rainfall that has occurred north of 20°S in southern Africa

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